Fermi National Accelerator Laboratory

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CDF

A Measurement of the Ratio $\sigma \bullet B(p\bar{p} \to W \to e\nu)/\sigma \bullet B(p\bar{p} \to Z^0 \to ee)$ in $p\bar{p}$ Collisions at $\sqrt{s} = 1800$ GeV

F. Abe et al.
The CDF Collaboration

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

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F. Abe,[13] M. G. Albrow,[7] S.R. Amendolia,[23] D. Amidei,[16] J. Antos,[28] C. Anway-Wiese,[4] G. Apollinari,[26] H. Areti,[7] M. Atac,[7] P. Auchincloss,[25] F. Azfar,[21] P. Azzi,[20] N. Bacchetta,[18] W. Badgett,[16] M. W. Bailey,[18] J. Bao,[35] P. de Barbaro,[25] A. Barbaro-Galtieri,[14] V. E. Barnes,[24] B. A. Barnett,[12] P. Bartalini,[23] G. Bauer,[15] T. Baumann,[9] F. Bedeschi,[23] S. Behrends,[3] S. Belforte,[23] G. Bellettini,[23] J. Bellinger,[34] D. Benjamin,[33] J. Benlloch,[15] J. Bensinger,[3] D. Benton,[21] A. Beretvas,[7] J. P. Berge,[7] S. Bertolucci,[8] A. Bhatti,[26] K. Biery,[11] M. Binkley,[7] F. Bird,[29] D. Bisello,[20] R. E. Blair,[1] C. Blocker,[29] A. Bodek,[25] W. Bokhari,[15] V. Bolognesi,[23] D. Bortoletto,[24] C. Boswell,[12] T. Boulos,[14] G. Brandenburg,[9] C. Bromberg,[17] E. Buckley-Geer,[7] H. S. Budd,[25] K. Burkett,[16] G. Busetto,[20] A. Byon-Wagner,[7] K. L. Byrum,[1] J. Cammerata,[12] C. Campagnari,[7] M. Campbell,[16] A. Caner,[7] W. Carithers,[14] D. Carlsmith,[34] A. Castro,[20] Y. Cen,[21] F. Cervelli,[23] H.Y. Chao,[28] J. Chapman,[16] M.-T. Cheng,[28] G. Chiarelli,[8] T. Chikamatsu,[32] C.N. Chiou,[28] S. Cihangir,[7] A. G. Clark,[23] M. Cobal,[23] M. Contreras,[5] J. Conway,[27] J. Cooper,[7] M. Cordelli,[8] C. Couyoumtzelis,[23] D. Crane,[1] J. D. Cunningham,[3] T. Daniels[15] F. DeJongh,[7] S. Delchamps,[7] S. Dell'Agnello,[23] M. Dell'Orso,[23] L. Demortier,[26] B. Denby,[23] M. Deninno,[2] P. F. Derwent,[16] T. Devlin,[27] M. Dickson,[25] J. Dittman,[6] S. Donati,[23] R. B. Drucker,[14] A. Dunn,[16] K. Einsweiler,[14] J. E. Elias,[7] R. Ely,[14] E. Engels, Jr.,[22] S. Eno,[5] D. Errede,[10] S. Errede,[10] Q. Fan,[25] B. Farhat,[15] I. Fiori,[2] B. Flaugher,[7] G. W. Foster,[7] M. Franklin,[9] M. Frautschi,[18] J. Freeman,[7] J. Friedman,[15] H. Frisch,[5] A. Fry,[29] T. A. Fuess,[1] Y. Fukui,[13] S. Funaki,[32] G. Gagliardi,[23] S. Galeotti,[23] M. Gallinaro,[20] A. F. Garfinkel,[24] S. Geer,[7] D. W. Gerdes,[16] P. Giannetti,[23] N. Giokaris,[26] P. Giromini,[8] L. Gladney,[21] D. Glenzinski,[12] M. Gold,[18] J. Gonzalez,[21] A. Gordon,[9] A. T. Goshaw,[6] K. Goulianos,[26] H. Grassmann,[6] A. Grewal,[21] L. Groer,[27] C. Grosso-Pilcher,[5] C. Haber,[14] S. R. Hahn,[7] R. Hamilton,[9] R. Handler,[34] R. M. Hans,[35] K. Hara,[32] B. Harral,[21] R. M. Harris,[7] S. A. Hauger,[6] J. Hauser,[4] C. Hawk,[27] J. Heinrich,[21] D. Cronin-Hennessy,[6] R. Hollebeek,[21] L. Holloway,[10] A. Hölscher,[11] S. Hong,[16] G. Houk,[21] P. Hu,[22] B. T. Huffman,[22] R. Hughes,[25] P. Hurst,[9] J. Huston,[17] J. Huth,[9] J. Hylen,[7] M. Incagli,[23] J. Incandela,[7] H. Iso,[32] H. Jensen,[7] C. P. Jessop,[9] U. Joshi,[7] R. W. Kadel,[14] E. Kajfasz,[7a] T. Kamon,[30] T. Kaneko,[32] D. A. Kardelis,[10] H. Kasha,[35] Y. Kato,[19] L. Keeble,[30] R. D. Kennedy,[27] R. Kephart,[7] P. Kesten,[14] D. Kestenbaum,[9] R. M. Keup,[10] H. Keutelian,[7] F. Keyvan,[4] D. H. Kim,[7] H. S. Kim,[11] S. B. Kim,[16] S. H. Kim,[32] Y. K. Kim,[14] L. Kirsch,[3] P. Koehn,[25] K. Kondo,[32] J. Konigsberg,[9] S. Kopp,[5] K. Kordas,[11] W. Koska,[7] E. Kovacs,[7a] W. Kowald,[6] M. Krasberg,[16] J. Kroll,[7] M. Kruse,[24] S. E. Kuhlmann,[1] E. Kuns,[27] A. T. Laasanen,[24] N. Labanca,[23] S. Lammel,[4] J. I. Lamoureux,[3] T. LeCompte,[10] S. Leone,[23] J. D. Lewis,[7] P. Limon,[7] M. Lindgren,[4] T. M. Liss,[10] N. Lockyer,[21] C. Loomis,[27] O. Long,[21] M. Loreti,[20] E. H. Low,[21] J. Lu,[30] D. Lucchesi,[23] C. B. Luchini,[10] P. Lukens,[7] J. Lys,[14] P. Maas,[34] K. Maeshima,[7] A. Maghakian,[26] P. Maksimovic,[15] M. Mangano,[23] J. Mansour,[17] M. Mariotti,[20] J. P. Marriner,[7] A. Martin,[10] J. A. J. Matthews,[18] R. Mattingly,[15] P. McIntyre,[30] P. Melese,[26] A. Menzione,[23] E. Meschi,[23] G. Michail,[9] S. Mikamo,[13] M. Miller,[5] R. Miller,[17] T. Mimashi,[32] S. Miscetti,[8] M. Mishina,[13] H. Mitsushio,[32] S. Miyashita,[32] Y. Morita,[13] S. Moulding,[26] J. Mueller,[27] A. Mukherjee,[7] T. Muller,[4] P. Musgrave,[11] L. F. Nakae,[29] I. Nakano,[32] C. Nelson,[7] D. Neuberger,[4] C. Newman-Holmes,[7] L. Nodulman,[1] S. Ogawa,[32] S. H. Oh,[6] K. E. Ohl,[35] R. Oishi,[32] T. Okusawa,[19] C. Pagliarone,[23] R. Paoletti,[23] V. Papadimitriou,[31] S. Park,[7] J. Patrick,[7] G. Pauletta,[23] M. Paulini,[14] L. Pescara,[20] M. D. Peters,[14] T. J. Phillips,[6] G. Piacentino,[2] M. Pillai,[25] R. Plunkett,[7] L. Pondrom,[34] N. Produit,[14] J. Proudfoot,[1] F. Ptohos,[9] G. Punzi,[23] K. Ragan,[11] F. Rimondi,[2] L. Ristori,[23] M. Roach-Bellino,[33] W. J. Robertson,[6] T. Rodrigo,[7] J. Romano,[5] L. Rosenson,[15] W. K. Sakumoto,[25] D. Saltzberg,[5] A. Sansoni,[8] V. Scarpine,[30] A. Schindler,[14] P. Schlabach,[9] E. E. Schmidt,[7] M. P. Schmidt,[35] O. Schneider,[14]

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G. F. Sciacca,[23] A. Scribano,[23] S. Segler,[7] S. Seidel[18] Y. Seiya,[32] G. Sganos,[11] A. Sgolacchia,[2] M. Shapiro,[14] N. M. Shaw,[24] Q. Shen,[24] P. F. Shepard,[22] M. Shimojima,[32] M. Shochet,[5] J. Siegrist,[29] A. Sill,[31] P. Sinervo,[11] P. Singh,[22] J. Skarha,[12] K. Sliwa,[33] D. A. Smith,[23] F. D. Snider,[12] L. Song,[7] T. Song,[16] J. Spalding,[7] L. Spiegel,[7] P. Sphicas,[15] A. Spies,[12] L. Stanco,[20] J. Steele,[34] A. Stefanini,[23] K. Strahl,[11] J. Strait,[7] D. Stuart,[7] G. Sullivan,[5] K. Sumorok,[15] R. L. Swartz, Jr.,[10] T. Takahashi,[19] K. Takikawa,[32] F. Tartarelli,[23] W. Taylor,[11] Y. Teramoto,[19] S. Tether,[15] D. Theriot,[7] J. Thomas,[29] T. L. Thomas,[18] R. Thun,[16] M. Timko,[33] P. Tipton,[25] A. Titov,[26] S. Tkaczyk,[7] K. Tollefson,[25] A. Tollestrup,[7] J. Tonnison,[24] J. F. de Troconiz,[9] J. Tseng,[12] M. Turcotte,[29] N. Turini,[2] N. Uemura,[32] F. Ukegawa,[21] G. Unal,[21] S. van den Brink,[22] S. Vejcik, III,[16] R. Vidal,[7] M. Vondracek,[10] R. G. Wagner,[1] R. L. Wagner,[7] N. Wainer,[7] R. C. Walker,[25] C.H. Wang,[28] G. Wang,[23] J. Wang,[5] M. J. Wang,[28] Q. F. Wang,[26] A. Warburton,[11] G. Watts,[25] T. Watts,[27] R. Webb,[30] C. Wendt,[34] H. Wenzel,[14] W. C. Wester III,[14] T. Westhusing,[10] A. B. Wicklund,[1] E. Wicklund,[7] R. Wilkinson,[21] H. H. Williams,[21] P. Wilson,[5] B. L. Winer,[25] J. Wolinski,[30] D. Y. Wu,[16] X. Wu,[23] J. Wyss,[20] A. Yagil,[7] W. Yao,[14] K. Yasuoka,[32] Y. Ye,[11] G. P. Yeh,[7] P. Yeh,[28] M. Yin,[6] J. Yoh,[7] T. Yoshida,[19] C. Yousef,[17] D. Yovanovitch,[7] I. Yu,[35] J. C. Yun,[7] A. Zanetti,[23] F. Zetti,[23] L. Zhang,[34] S. Zhang,[16] W. Zhang,[21] and S. Zucchelli[2]

(CDF Collaboration)

[1]Argonne National Laboratory, Argonne, Illinois 60439
[2]Istituto Nazionale di Fisica Nucleare, University of Bologna, I-40126 Bologna, Italy
[3]Brandeis University, Waltham, Massachusetts 02254
[4]University of California at Los Angeles, Los Angeles, California 90024
[5]University of Chicago, Chicago, Illinois 60637
[6]Duke University, Durham, North Carolina 27708
[7]Fermi National Accelerator Laboratory, Batavia, Illinois 60510
[8]Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy
[9]Harvard University, Cambridge, Massachusetts 02138
[10] University of Illinois, Urbana, Illinois 61801
[11]Institute of Particle Physics, McGill University, Montreal H3A 2T8, and University of Toronto, Toronto M5S 1A7, Canada
[12]The Johns Hopkins University, Baltimore, Maryland 21218
[13]National Laboratory for High Energy Physics (KEK), Tsukuba, Ibaraki 305, Japan
[14]Lawrence Berkeley Laboratory, Berkeley, California 94720
[15]Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
[16]University of Michigan, Ann Arbor, Michigan 48109
[17]Michigan State University, East Lansing, Michigan 48824
[18]University of New Mexico, Albuquerque, New Mexico 87131
[19]Osaka City University, Osaka 588, Japan
[20]Universita di Padova, Instituto Nazionale di Fisica Nucleare, Sezione di Padova, I-35131 Padova, Italy
[21]University of Pennsylvania, Philadelphia, Pennsylvania 19104
[22]University of Pittsburgh, Pittsburgh, Pennsylvania 15260
[23]Istituto Nazionale di Fisica Nucleare, University and Scuola Normale Superiore of Pisa, I-56100 Pisa, Italy
[24]Purdue University, West Lafayette, Indiana 47907
[25]University of Rochester, Rochester, New York 14627
[26]Rockefeller University, New York, New York 10021
[27]Rutgers University, Piscataway, New Jersey 08854
[28]Academia Sinica, Taiwan 11529, Republic of China
[29]Superconducting Super Collider Laboratory, Dallas, Texas 75237
[30]Texas A&M University, College Station, Texas 77843
[31]Texas Tech University, Lubbock, Texas 79409
[32]University of Tsukuba, Tsukuba, Ibaraki 305, Japan
[33]Tufts University, Medford, Massachusetts 02155
[34]University of Wisconsin, Madison, Wisconsin 53706
[35]Yale University, New Haven, Connecticut 06511
[a]Visitor

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Abstract

We present an analysis of data from $p\overline{p}$ collisions at a center of mass energy of $\sqrt{s}$ = 1800 GeV. A measurement is made of the ratio $R \equiv \sigma{\cdot}B(p\overline{p}\rightarrow W\rightarrow e\nu)\ /\ \sigma{\cdot}B(p\overline{p}\rightarrow Z^0\rightarrow ee)$. The data represent 19.6 pb^{-1} collected by the Collider Detector at Fermilab (CDF) during the 1992-1993 collider run of the Fermilab Tevatron. We find R = 10.90 ± 0.32 (*stat.*) ± 0.29 (*sys.*), and from this value we extract a measurement of the $W\rightarrow e\nu$ branching ratio $\Gamma(W\rightarrow e\nu)/\Gamma(W)$ = 0.1094 ± 0.0033(*stat.*) ± 0.0031(*sys.*). From this branching ratio we set a limit on the top quark mass of m_{top} > 62 GeV/c^2 at the 95% confidence level. In contrast to direct searches for the top quark, this limit makes no assumptions about the allowed decay modes of the top quark. In addition, we use a calculation of the leptonic width $\Gamma(W\rightarrow e\nu)$ to obtain a value for the W total decay width: $\Gamma(W)$ = 2.064 ±0.060(*stat.*) ± 0.059(*sys.*) GeV.

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1. Introduction

The W boson width, $\Gamma(W)$, is a fundamental parameter that is well-predicted in the Standard Model. The W decays with approximately equal probability to each of three lepton families and to the two quark families that are kinematically available. The quark families receive an additional factor of three in their decay probabilities due to their color charge. Hence, the branching ratio of the W into $(\ell,\overline{\nu}_\ell)$ is approximately $\frac{1}{9}$. By dividing a calculation of the W leptonic partial width, $\Gamma(W\rightarrow\ell\nu)$, by the leptonic branching ratio, one may predict that the W width is ≈ 2.1 GeV. This article presents a measurement of W boson decay width, $\Gamma(W)$, and of the leptonic branching ratio, $\Gamma(W\rightarrow e\nu)/\Gamma(W)$.

The W width is altered if additional decay modes are available to the W. In particular, if the W can decay to a light top quark ($m_t < M_W - m_b$) and a b quark, the W

width changes to $\Gamma(W) \approx 2.8\ GeV$ and the leptonic branching ratio changes to $\Gamma(W \to \ell\nu)/\Gamma(W) \approx 1/12$. Direct searches[1] have set a limit of $m_t > 131\ GeV/c^2$ (95% C.L.), but these limits assume that the top always decays via the reaction $t \to Wb$. We have presented evidence[2] that suggests that the top quark mass is $m_t = 174 \pm 17\ GeV/c^2$. If, however, the top is light and has decays other than $t \to Wb$ that have been missed by the direct searches, or if other weak isodoublets exist that couple to the W, then the W width could see a contribution from these sources. The top could have non-Standard Model decays, for example, if a charged Higgs exists and $t \to H^+ b$ were the dominant decay channel. Then the top could be missed by direct searches for $t \to Wb$.[3] These enhancements to the W width are independent of assumptions regarding the allowed decays of the daughters of the W.

The W decays with universal coupling to pairs of fermions within weak isodoublets. The partial width into fermion pairs is calculated to be:[4] $\Gamma_0(W \to f\bar{f}') = |V_{ff'}|^2 N_c\, g^2 M_W/48\pi$, where $V_{ff'}$ is the CKM matrix element for two quarks and is 1.0 for leptons. The color factor N_c is 3 for quarks and is 1 for leptons. The variable M_W is the W boson mass, and g is the W's coupling to fermions. In the Standard Model the W-fermion coupling is given by $g^2 = \frac{8}{\sqrt{2}} G_F M_W^2$, where G_F is the Fermi coupling constant derived from the muon lifetime.

This simple calculation of the W width receives corrections at next-to-leading order in QCD. At lowest order, the W may decay with equal probability to each of three lepton families and to two quark families, assuming that the top quark is heavy (with a color factor of three on the quark decays). Quark decays receive an additional QCD K-factor enhancement at $O(\alpha_s)$ due to vertex graphs involving gluon exchange. Rosner *et al.*[5] have thus calculated:

$$\Gamma_0(W \to \ell\nu)/\Gamma_0(W) = [3 + 6(1 + \alpha_s(M_W)/\pi)]^{-1} = 0.1084 \pm 0.0002.$$

$$\Gamma_0(W) = 2.075 \pm 0.021\ GeV,$$

The W width also receives electroweak corrections due to next-to-leading order graphs which alter the effective coupling g at the W-fermion vertex for all fermions. Within the context of the Standard Model the W width receives vertex and

Bremsstrahlung corrections[4] that depend upon the top and Higgs masses. The corrections can be summarized in the equation:

$$\Gamma(W \to f\bar{f}')_{SM} = \Gamma_0(W \to f\bar{f}') \cdot \left[1 + \delta_V + \delta_W(0) + \delta_\mu\right],$$

where $\delta_W(0)$ is the correction to the width from loops at the W-fermion vertex involving Z^0's or a Standard Model Higgs, δ_V describes boson self-energies, and δ_μ is a correction made necessary when g is parameterized using the W mass and the value of G_F from muon decay.[6] The factor $\delta_W(0)$ also incorporates corrections to the W propagator from the top quark that are not absorbed into the W mass. The vertex corrections from the Standard Model Higgs cause $\Gamma(W)$ to change by approximately 1% as the Higgs mass varies from 50 GeV/c^2 to 1000 GeV/c^2, while the correction from $\bar{t}\bar{b}$ loops changes $\Gamma(W)$ by approximately 4% as the top quark mass varies from 80 GeV/c^2 to 200 GeV/c^2.[4]

Because the electroweak vertex corrections to g above are nearly identical for both leptons and quarks, these corrections affect only the W width. In the case of the leptonic branching ratio, the coupling g cancels out and hence the leptonic branching ratio is almost competely insensitive to these vertex corrections. Including the radiative corrections, and for the particular choice of $m_t = 140\ GeV/c^2$ and $M_{Higgs} = 100\ GeV/c^2$, Rosner, *et al.*, find:[5]

$$\Gamma(W)_{SM} = 0.996 \times \Gamma_0(W) = 2.067 \pm 0.021\ GeV,$$

$$\Gamma(W \to \ell\nu)_{SM} \,/\, \Gamma(W)_{SM} = \Gamma_0(W \to \ell\nu) \,/\, \Gamma_0(W) = 0.1084 \pm 0.0002.$$

To test the Standard Model, it is desirable to measure both $\Gamma(W \to \ell\nu)/\Gamma(W)$ and $\Gamma(W)$. The branching ratio is the most sensitive quantity for new decay modes, since the uncertainty in the theoretical prediction of $\Gamma(W)$ due to the uncertainty in the measured W mass cancels in the branching ratio. The total width, furthermore, may be used along with the leptonic branching ratio to obtain a measure of $\Gamma(W \to \ell\nu)$. The leptonic partial width is predicted to be $g^2 M_W/48\pi$, and deviations in the measured value indicate values of the W-fermion coupling g^2 different from that given by the Standard Model.

1.1 Measurement of $\Gamma(W)$ from W and Z^0 Cross Sections

The W leptonic branching ratio may be extracted from a measurement of the ratio, R, of the cross sections times leptonic branching ratios of the W and Z^0 in $p\overline{p}$ collisions.[7] The ratio R may be expressed as:

$$R \equiv \frac{\sigma \cdot B(p\overline{p}\to W\to \ell\nu)}{\sigma \cdot B(p\overline{p}\to Z^0\to \ell\ell)} = \frac{\sigma(p\overline{p}\to W)}{\sigma(p\overline{p}\to Z^0)} \; \frac{\Gamma(W\to\ell\nu)}{\Gamma(Z^0\to\ell\ell)} \; \frac{\Gamma(Z^0)}{\Gamma(W)}$$

On the right hand side, the ratio $\sigma(p\overline{p}\to W) / \sigma(p\overline{p}\to Z^0)$ of the production cross sections may be calculated from the boson couplings and knowledge of the proton structure. The Z^0 total width, $\Gamma(Z^0)$, and the leptonic partial width, $\Gamma(Z^0\to\ell^+\ell^-)$, are well-measured by the LEP experiments.[8] Thus, a measurement of R yields a precise measurement of the W leptonic branching ratio $\Gamma(W\to\ell\nu)/\Gamma(W)$. If one then divides a calculation of the leptonic width $\Gamma(W\to\ell\nu)$ by the measured branching ratio, a value is extracted for the total decay width, $\Gamma(W)$, of the W. Note, however, that the width extracted from the branching ratio is not sensitive to electroweak vertex corrections to the coupling g, since it is normalized to the calculated $\Gamma(W\to\ell\nu)$. While in principle the corrections to the W-fermion coupling would also alter the production cross section $\sigma(p\overline{p}\to W)$, a direct measurement of $\Gamma(W)$, such as the one described in Section 1.2, is desirable as a check of these effects.

1.2 Previous Measurements of $\Gamma(W)$

The measurements of the W width extracted from the ratio R are given in Table 1.1. In Table 1.1, mode = "e" or "μ" refers to the decay mode of the W (or Z^0) used in the measurement. This long paper reports on a measurement of R made by the CDF Collaboration[9] with a relative uncertainty of 4.1%. The best measurement of the W width previous to the most recent CDF result has an error of 7.6%. The combination of all published measurements from R yields a value for the W total decay width, $\Gamma(W) = 2.07 \pm 0.07$ GeV, an accuracy of 3.5%. Prior to the most recent CDF measurement, the world average had an uncertainty of 5.2%.

The W width has also been measured directly from studies of the W transverse mass lineshape in $p\bar{p}$ collisions, where $M_T^2 \equiv (|\vec{p}_T^{\,e}| + |\vec{p}_T^{\,\nu}|)^2 - (\vec{p}_T^{\,e} + \vec{p}_T^{\,\nu})^2$ and $\vec{p}_T^{\,e}$ and $\vec{p}_T^{\,\nu}$ are components of the electron and neutrino momenta transverse to the p and $\bar{p}$ beams. These direct measurements complement the indirect value from the W and Z^0 cross sections because they have entirely different systematic uncertainties. More importantly, they are free of the theoretical assumptions regarding the W

Table 1.1: Previous Measurements of $\Gamma(W)$.

Experiment	Method	Mode	$\sqrt{s}$ (TeV)	$\Gamma(W)$ (GeV)
CDF[9]	R	e	1.8	2.064 ± 0.085
CDF[10]	R	e	1.8	2.14 ± 0.20
CDF[11]	R	μ	1.8	2.21 ± 0.27
UA1[12]	R	μ	0.63	2.19 ± 0.30
UA2[13]	R	e	0.63	2.10 ± 0.16
UA1[14]	Direct	e	0.63	2.8 ± 1.9
CDF[15]	Direct	e	1.8	2.11 ± 0.32

coupling to fermions. Direct measurements of $\Gamma(W)$ from the transverse mass distribution at hadron colliders will approach the 1% level with the 1 fb^{-1} of data anticipated at Fermilab in 1998.[16]

The W width will also be determined by the LEP-200 experiments at center of mass energy near $\sqrt{s} = 2M_W$ from an endpoint analysis of the W daughter lepton energy spectrum. This measurement of $\Gamma(W)$ is also direct one, like the lineshape measurements at $p\bar{p}$ colliders, and the LEP-200 experiments anticipate an accuracy on $\Gamma(W)$ of 200 MeV, or 10%.[17]

1.3 1992-1993 Run of CDF

The data presented in this paper were collected by the Collider Detector at Fermilab observing $p\bar{p}$ collisions at a center of mass energy of $\sqrt{s} = 1.8$ TeV. During the 1992-1993 collider run, the Fermilab Tevatron delivered a total integrated luminosity of $\int L dt = 27.3$ pb^{-1}, with typical instantaneous luminosities of 4.0×10^{30} $cm^{-2}sec^{-1}$ and a peak instantaneous luminosity of 9.7×10^{30} $cm^{-2}sec^{-1}$. The Collider Detector at Fermilab wrote 20.6 pb^{-1} of data to tape, with the 30% loss dominated by operational problems. This compares to 4.0 pb^{-1} of data collected in

CDF's previous 1988-1989 run. Approximately 1.0 pb^{-1} of this year's data was discarded after the fact because of hardware difficulties during data taking. In the 19.6 pb^{-1} of data remaining, approximately 20000 $W \rightarrow e\nu$ and 1600 $Z^0 \rightarrow e^+e^-$ decays were observed from all triggers, as were 7000 $W \rightarrow \mu\nu$ and 600 $Z^0 \rightarrow \mu^+\mu^-$ decays. Note that, while same data sample is being reported on as in reference [9], our measurement of the luminosity has changed by approximately 10%. This change is documented in reference [2]. Thus, while reference [9] quotes an integrated luminosity of 21.7 pb^{-1}, that same data sample is here estimated as 19.6 pb^{-1}. Note that R is independent of the luminosity.

1.4 Strategy of This Measurement

The signature of high-P_T leptons from W and Z^0 decay is quite distinctive in the environment of hadron collisions. As such, the decay of W and Z^0 bosons into leptons provides a clean experimental measurement of their production. Experimentally, the cross sections times branching ratios are found from:

$$\sigma \cdot B(p\overline{p} \rightarrow W \rightarrow \ell\nu) = \frac{N_W^{Candidates} - N_W^{Background}}{A_W \varepsilon_W \int L dt}$$

$$\sigma \cdot B(p\overline{p} \rightarrow Z^0 \rightarrow \ell^+\ell^-) = \frac{N_Z^{Candidates} - N_Z^{Background}}{A_Z \varepsilon_Z \int L dt}$$

where $N_W^{Candidates}$ and $N_Z^{Candidates}$ are the number of W and Z^0 candidates observed; A_W and A_Z are the "acceptance" for the W and Z^0 decays (which includes the efficiency for the kinematic cuts on the leptons and the geometric acceptance of the detector); ε_W and ε_Z are the efficiency for the W and Z^0 to pass the lepton identification criteria, and $\int L dt$ is the integrated luminosity of the experiment. Measuring the ratio of the cross sections allows some of the quantities (as well as their uncertainties) on the right hand sides to cancel.

The strategy of this cross section ratio measurement will be to require at least one charged lepton passing tight selection criteria in both W and Z^0 decays to fall in the central, barrel region of the detector, where magnetic tracking analysis augments the calorimeter measurements (See Section 2). For this measurement, only electrons will be considered.

The number of Z^0's limits the statistical accuracy of the R measurement of $\Gamma(W)$, and this tactic of requiring a central electron common to both W and Z^0 decays decreases the available Z^0 statistics even further. From a simple Monte Carlo (described in Section 7), we learn that this requirement is approximately 80% efficient for Z^0's. It is only ~ 60% efficient for W's, but the W's do not statistically limit the overall measurement. Requiring a common central electron for both W's and Z^0's will increase the statistical error on R from 2.6% to 2.9%.

This method of requiring one central electron common to both W and Z^0 decays, however, decreases the systematic error in the measurement. The selection criteria for the central electron (which appear in the factors ε_W and ε_Z) will almost completely cancel in the ratio R because they are common to W's and Z^0's. Imposing tight selection criteria on the central lepton allows loose selection criteria to be applied on the second lepton (either electron or neutrino). The systematic error in the ratio of acceptances is also smaller than for the individual acceptances when a common central electron is required. Furthermore, because of the magnetic analysis in the barrel region of the detector, systematic errors from W and Z^0 backgrounds are much smaller in the barrel than in the end-cap regions. These smaller uncertainties offset the expected 0.3% increase in statistical error from requiring the common central electron.

1.5 Electrons in $p\ \overline{p}$ Collisions

In addition to presenting a measurement of the W/Z^0 cross section ratio in $p\overline{p}$ collisions, this paper attempts to describe the other sources of inclusive electrons. Electrons from W and Z^0 decay account for only a fraction of the high-P_T inclusive electrons observed in our detector, and the study of these other electrons is not only of interest in determining the backgrounds to the W/Z^0 samples, but of interest in its own right. We anticipate that electrons in $p\overline{p}$ collisions fall into three categories: 1) electrons which come in e^+e^- pairs, either from photon conversions or Dalitz decays; 2) electrons from heavy quark decay; and 3) hadrons that fake electrons. We discuss techniques to diffentiate between these different sources of electrons and their relative contributions to the inclusive electrons observed.

1.6 Outline of Paper

The article will proceed as follows: Section 2 describes electron and neutrino identification in the CDF detector. Section 3 describes the selection of the inclusive electron sample and the separation of this sample into W and Z^0 samples and a non-W/Z^0 control sample of electrons. Section 4 describes the physics sources of high-P_T electrons in the non-W/Z^0 sample. This description is used in Section 5, where we discuss the make-up of the W sample and estimate the backgrounds. Section 6 discusses the Z^0 candidate sample and its backgrounds. Section 7 describes the Monte Carlo program used to determine the acceptance ratio A_W/A_Z. Section 8 describes the the efficiencies ε_W and ε_Z. Section 9 provides a cross check of the R measurement, and Section 10 summarizes the extraction of $\Gamma(W)$ from the cross sections.

2. Electron and Neutrino Identification

Many previous publications[18] give detailed descriptions of the various components of the Collider Detector at Fermilab (CDF) detector. In this section, we summarize briefly the physical characteristics of those detector components relevant for electron and neutrino identification and describe their performance during the 1992-1993 run.

2.1 The CDF Detector

CDF is a cylindrical detector with a central barrel region, two end-cap (plug) regions closing the barrel, and two far-forward detector regions (see Figure 2.1). It features electromagnetic (EM) and hadronic (Had) shower counters arranged in projective tower geometry, as well as charged particle tracking chambers. The tracking chambers are immersed in a 1.4 T magnetic field oriented along the proton beam direction provided by a 3 m diameter, 5 m long superconducting solenoidal magnet coil. Although not used in this analysis, drift chambers outside the hadron calorimeters for muon detection cover the region $|\eta| < 1.0$.[19]

2.1.2 Calorimeters

Table 2.1 summarizes the calorimeter subsystems at CDF. In the central barrel region covering the angular region $-1.1 < \eta < 1.1$, the electromagnetic (CEM) and hadron (CHA, WHA) calorimeters are made of absorber sheets interspersed with scintillator. Plastic light guides bring the light up to two phototubes per EM tower. The towers are constructed in 48 wedges, each consisting of 10 towers in η by one tower in ϕ (see Figure 2.2). Proportional chambers are embedded near shower maximum, 6 radiation lengths (X_0) within the EM calorimeters. These chambers, called Central Electron Strip (CES) chambers, have wires in the r-ϕ view and cathode strips in the z view. The CES is summarized in Table 2.2. A second set of proportional chambers, the Central Pre-Radiator (CPR), placed in between the front face of the EM calorimeters and the magnet coil, act as a shower pre-sampler. Both the CES and CPR are split into two separate readout segments in the z direction, so that the wires do not run along the full length of the calorimeter, but are read out in two divisions.

In the plug end-cap and forward detector regions, the towers are made of absorber sheets sandwiched with conductive plastic proportional tube arrays. Cathode strips outside the plastic tubes are read out and provide tower segmentation. Near shower maximum in the plug EM (PEM) calorimeter, a layer with finer-spaced strips spacing provides shower profile and precise position determination.

Arrays of scintillator planes are mounted on the front face of each of the far-forward EM shower counters. These planes, called the Beam-Beam Counters (BBC's) are shown in Figure 2.1 and are used to signal an inelastic collision. At lower instantaneous luminosities, a coincidence of at least one hit in each plane of the BBC's is required to initiate the trigger system. Each BBC consists of an array of 16 scintillator planes and 16 photomultiplier tubes that encircle the 360° around beam pipe and cover the pseudorapidity range $3.24 < |\eta| < 5.90$. At higher instantaneous luminosities, the mean number of $p\overline{p}$ interactions per crossing of p and $\overline{p}$ bunches is sufficiently high that the BBC coincidence was unnecessary to guarantee the presence of an inelastic collision.

Table 2.1 Description of the CDF Calorimeter Subsystems

	CEM	CHA,WHA	PEM	PHA	FEM	FHA
Energy Resolution ($\% / \sqrt{E}$)	13.5	80	28	130	25	141
Angular Coverage (in $\lvert\eta\rvert$)	< 1.1	< 1.3	1.1 - 2.4	1.3 - 2.4	2.2 - 4.2	2.3 - 4.2
Segmentation ($\Delta\eta \times \Delta\phi$)	$0.1 \times 15°$	$0.1 \times 15°$	$0.1 \times 5°$	$0.1 \times 5°$	$0.1 \times 5°$	$0.1 \times 5°$
Active Medium	lead, scintil-lator	iron, scintil-lator	lead, propor-tional tube	iron, propor-tional tube	lead, propor-tional tube	iron, propor-tional tube
Position Resolution (r-$\phi \times z$)	0.2 cm × 0.2 cm[a]	10 cm × 5 cm	0.2 cm × 0.2 cm	2 cm × 2 cm	0.2 cm × 0.2 cm	3 cm × 3 cm
Longitudinal Depth	18 X_0,[b] 1.0 Λ_{abs}	4.7 Λ_{abs}	19 X_0, 1.0 Λ_{abs}	5.7 Λ_{abs}	25 X_0, 0.8 Λ_{abs}	7.7 Λ_{abs}

a) Using the CES chambers b) Including the 1 X_0 solenoidal coil

Table 2.2 Description of the Shower Max Detector (CES) and Pre-Shower Detector (CPR).

	CES Chamber		CPR Chamber
	Wires (r-ϕ view)	Strips (z view)	Wires (r-ϕ view)
Number of Channels	32	69,[a] 59[b]	16
Spacing (cm)	1.45	1.67,[a] 2.07[b]	2.2
Spatial Resolution (cm)	0.2	0.2	-
Saturation Energy (GeV)	150	150	>150
Chamber length in z (cm)	234		103
Chamber Width in ϕ (°)	14.0		12.1

a) for CES segment between 6 cm < z < 115 cm
b) for CES segment between 115 cm < z < 240 cm

2.1.2 *Charged Particle Tracking*

Within the 1.4 T axial magnetic field of the solenoidal magnet are three detectors for charged particle tracking. The Silicon Vertex Detector (SVX) is a four-layer silicon microvertex detector with single-sided readout to provide precise r-ϕ information for the reconstruction of track impact parameters. The Vertex Tracking Chamber (VTX) is a time projection chamber in 8 modules with a maximum drift distance of 10 *cm*. It provides reconstruction of the primary event vertex in the z direction with $\sigma_z = 1$ *mm* accuracy. The Central Tracking Chamber (CTC) is a large drift chamber with 84 layers of sense wires organized into 9 superlayers. Four of the superlayers are tilted $\pm$ 3° with respect to the z axis so as to provide stereo position measurement of charged particle tracks. The charge collected on its wires allow particle identification to be performed through *dE/dx* measurements with 1.5σ e-π separation at 5 *GeV/c*. The three tracking chambers are summarized in Table 2.3.

Table 2.3: Description of the Charged Particle Tracking Chambers

	Silicon Vertex Detector (SVX)	Vertex Tracking Chamber (VTX)	Central Tracking Chamber (CTC)
Polar Angle Coverage	$\lvert\eta\rvert < 1.0$	$\lvert\eta\rvert < 3.25$	$\lvert\eta\rvert < 1.5$
Inner, Outer Tracking Radii (cm)	2.7, 7.9	8, [a] 22	30.9, 132.0
Length (cm)	26	280	320
Layers	4	24	60 axial, 24 stereo
Strip or Wire Spacing	60 μm (inner 3 lay.) 55 μm (outer layer)	6.3 mm	10 mm
Spatial Resolution	15 μm (r-ϕ)	200-500 μm (r-z)	200 μm (r-ϕ) 4 mm (r-z)
Momentum Resolution	$\delta P_T/P_T = 0.001 \times P_T$ [b]	-	$\delta P_T/P_T = 0.002 \times P_T$
Thickness ($\theta = 90°$)	$\approx 0.035\ X_0$	$\approx 0.045\ X_0$	$\approx 0.015\ X_0$

[a] For inner 2 modules. Outer 6 modules are 3 cm inner radius.
[b] With both CTC and SVX hits incorporated into track fit.

2.2 Electron Cluster Candidates

Electron identification begins with a clustering algorithm to identify electron showers. An electron cluster consists of a seed tower (the tower in the cluster with the largest energy) and shoulder towers (adjacent towers incorporated into the cluster). Towers with electromagnetic (EM) transverse energy $E_T > 3\ GeV$ are eligible to be seed towers.[20] Towers with EM $E_T > 0.1\ GeV$ are eligible to be shoulder towers. Beginning with each seed tower, a cluster is formed by incorporating neighboring shoulder towers until either no further adjacent towers may be incorporated or until the maximum cluster size is reached. The maximum cluster size is restricted to three towers in pseudorapidity ($\Delta\eta \approx 0.3$) by one tower in azimuth ($\Delta\phi \approx 15°$) in the central region, five towers in pseudorapidity ($\Delta\eta \approx 0.5$) by five towers in azimuth ($\Delta\phi \approx 25°$) in the plug region, and seven towers in pseudorapidity ($\Delta\eta \approx 0.6$) by seven towers in azimuth ($\Delta\phi \approx 35°$) in the forward region. Finally, it is required that the EM E_T of the cluster be greater than 5 GeV and that the ratio of hadronic E_T to electromagnetic E_T be less than 0.125.[21]

2.3 Fiducial Volume for Electrons

Figure 2.3 shows schematically the fiducial volume of the detector for electrons used in this analysis. Of the central region defined by $|\eta| < 1.1$, 78.9% of the area in η-ϕ space is in the fiducial volume for electrons; 78.5% of the region $|\eta| < 3.6$ is in the fiducial volume for electrons.

In the central region, the electron position is determined using the CES shower position and is required to lie within 21 cm of the tower center in the r-ϕ view so that the shower is fully contained in the active region. The region $|\eta| < 0.05$, where the two halves of the detector meet, is excluded. The region $0.77<\eta<1.0$, $75°<\phi<90°$ (the "chimney") is uninstrumented because it is the penetration for the cryogenic connections to the solenoidal magnet. In addition, the region $1.05 < |\eta| < 1.10$ is excluded because of the smaller depth of the electromagnetic calorimeter in this region.

In the plug and forward regions, the electron position is determined from the seed tower (see Section 2.1). The boundaries between detector regions, $1.1 < |\eta| < 1.2$

and 2.2 $< |\eta| <$ 2.4 are excluded because of the overlap between detectors. The region 3.6 $< |\eta| <$ 4.2 in the forward region is excluded. In both the plug and forward calorimeter, the electron seed tower is required not to be adjacent to the quadrant boundaries. This is $\pm$ 5° around each quadrant boundary.

2.4 Central Electron Identification

Electron identification in the central region is made more powerful by the presence of the Central Tracking Chamber, the Central Strip Chambers, and the Central Pre-Radiator. Using the electron identification variables described here and the cut values in Table 3.1 for tight central electron candidates, the fraction of hadron jets falsely identified as electrons is estimated to be 2×10^{-5} for jets with $E_T > 20$ GeV (note at CDF that the dominant background to high-P_T electron candidates is not isolated pions, but jets of hadrons). The CPR may be used to further reduce the misidentification rate by one order of magnitude. The purity of electron candidates with $E_T > 20$ GeV with the cuts of Table 3.1 is approximately 84%.

2.4.1 Calorimeter Transverse Profile

The transverse profile, or "*Lshr*," of a central electron allows a comparison of the lateral sharing of energy in the calorimeter towers of an electron cluster to electron shower shapes from test beam data. The variable *Lshr* is defined as:

$$Lshr = 0.14 \cdot \sum_i \frac{E_i^{Adj} - E_i^{Prob}}{\sqrt{0.14^2 \cdot E + (\Delta E_i^{Prob})^2}}$$

where E_i^{Adj} is the measured energy (in GeV) in a tower adjacent to the seed tower, E_i^{Prob} is the expected energy (in GeV) in the adjacent tower, $0.14\sqrt{E}$ (in GeV) is the error on the energy measurement, and ΔE_i^{Prob} (in GeV) is the error on the energy estimate. E_i^{Prob} is calculated using a parameterization from test beam data. The distribution of *Lshr* for inclusive and W electrons is shown in Figure 2.4(a).

2.4.2 Strip Chamber Pulse Height

The CES chamber, embedded 6 radiation lengths into the central electromagnetic calorimeter, can be used to observe the longitudinal development of a shower. An electromagnetic shower in the calorimeters is generally initiated much earlier for an electron than for a hadron. Shown in Figure 2.5(a) is the variable $CES/p \equiv (\Sigma Q_i)/p$ for electrons and hadrons, where Q_i is the charge on a strip (in ADC counts), p is the track's momentum (in GeV/c), and the sum is over the 5 strips (z view) around the track's position extrapolated to the strip chambers.

2.4.3 Strip Chamber Pulse Height Shape

The pulse height shape in the CES is also used for electron identification. The pulse height shape is compared to test beam data using a χ^2 test. The variable χ^2_{strip} is the χ^2 of the fit of the energy deposited on the each of the 11 strips in z in the CES shower compared to the test beam shape. A similar variable χ^2_{wire} tests the energy deposition on the wires in the r-ϕ view. The variable χ^2_{strip} for inclusive electron candidates and for electrons from W decays is shown in Figure 2.4(b).

2.4.4 Charged Track Requirement

Electromagnetic clusters in the calorimeters can arise from neutral particles, such as $\pi^0 \to \gamma\gamma$ decay. We require the presence of a charged track in the CTC for electron identification. We require the ratio of the electromagnetic energy, E, of the electron cluster measured in the calorimeter to the electron's momentum, p, measured in the central tracking chamber to lie in the range $0.5 < E/p < 2.0$. The distribution of the variable E/p for inclusive electron candidates and for electrons from W decays is shown in Figure 2.4(c). The tail above $E/p > 1$ in W electrons is due to the radiation of photons by the electron as they pass through the material inside the CTC. The radiated photons generally land in the same calorimeter cell as the electron, so E has the same value as the initial electron energy, but p is smaller as it is measured in the CTC after the Bremsstrahlung radiation. This tail is larger in the inclusive electrons because of the presence of electrons from $\pi^0 \to \gamma\gamma \to \gamma e^+ e^-$, for which p is the momentum of one electron, but E is close to the energy of the pion.

2.4.5 Track-Shower Matching Variables

The CTC track pointing to the electron cluster is extrapolated to the CES, and the extrapolated position is compared to the shower position as measured in the CES. The variable δx is the separation in the r-ϕ view between the extrapolated track position and the CES strip cluster position. The variable δz is the corresponding separation in the z view. Cutting on these variables reduces the background from overlaps of charged and neutral hadrons. The variables δx and δz for inclusive electron candidates and for electrons from W decays are shown in Figure 2.4(d,e).

2.4.6 CPR Pulse Height

The CPR pulse height on the two wires around a track is used to discriminate electrons from hadrons. An electron may begin to shower in the solenoid, while a hadron will leave only a minimum-ionizing pulse. The solenoidal coil thickness is 0.85 X_0 at normal incidence. Figure 2.5(b) shows the pulse height shapes for electrons and hadrons.

2.4.7 Electron Track Impact Parameter

The impact parameter of the electron's track is used to discriminate electrons of long-lived parent particles from those originating from primary vertex of the $p\overline{p}$ collision. The lifetime of bottom quarks is $c\tau \sim 400\,\mu m$, while the impact parameter, d_0, resolution is $\sigma_d \sim 40\,\mu m$. The lifetime of the W and Z^0 are negligible on this scale. For charged tracks with $P_T > 1\ GeV/c$, the dominant contribution to the impact parameter resolution is the uncertainty in the primary vertex position.

The "signed impact parameter," D_{sign}, is defined for a track in the CTC pointing to a jet in the calorimeters. It is defined as:

$$D_{sign} = d_0\left(\frac{\vec{d_0}\cdot\hat{n}_{jet}}{|\vec{d_0}\cdot\hat{n}_{jet}|}\right)$$

where $\vec{d_0}$ is the vector which points from the primary vertex to the point of closest approach of the track to the primary vertex. The unit vector $\hat{n}_{jet}$ points from the primary vertex to the energy centroid of the jet in the calorimeter. A track emanating from the decay vertex of a long-lived parent will have positive D_{sign}, whereas a track from the primary vertex will have, on average, zero D_{sign}.

The resolution effects which smear the observed D_{sign} spectrum are: the position resolution of the individual hits in the SVX layers; scattering of the electron in the beampipe before reaching the SVX; radiation of photons by the electron as it passes through the material in the tracking volume; and the location uncertainty of the primary vertex. The D_{sign} distribution for electrons from $Z^0 \rightarrow e^+e^-$ decays is shown in Figure 2.6. The observed σ agrees well with the dominant contributions of the $\sigma = 32.5\ \mu m$ effect of the primary vertex spread (see Figure 2.7), and the $\sigma = 10.7\ \mu m$ effect of Bremsstrahlung radiation (estimated from a Monte Carlo simulation). The impact parameter significance, $D/\sigma \equiv D_{sign}/\sigma$ is shown for electrons from $Z^0 \rightarrow e^+e^-$ decays in Figure 2.8 (a). Figure 2.8 (b) shows that the events in the tails are, in fact, Z^0's and not background. The non-gaussian D/σ tails come from accidental hits in the SVX incorrectly incorporated into the track fit.

2.4.8 Event Vertex Measurement

The position in z of the primary event vertex is measured by the Vertex Tracking Chamber (VTX). The z position of the event is distributed about the nominal interaction point by $\sigma = 26\ cm$ (see Figure 2.9). This spread is an average of many different σ's from different physics runs. The spread of the interaction point in z has implications for use of the SVX in physics analyses, since it is larger than the length of the SVX. From studying the tracks from Z^0 decays, 61.9 ± 1.3 % of primary vertices are contained within the SVX.

2.4.9 Leakage into the Hadronic Calorimeters

The ratio Had/EM of the energy in the hadronic towers of the electron cluster (Had) to the energy in the electromagnetic towers in the electron cluster (EM) is used to further select good electrons. The electromagnetic calorimeters nearly contain electromagnetic showers, while hadron showers in general deposit energy in both the hadronic and electromagnetic compartments. This quantity is physics-dependent, however, since isolated electrons have less hadronic energy near by them than would electrons produced in association with hadrons (such as electrons from semileptonic b decay, which in general are associated with a jet of hadrons from the decay of the charmed meson). The distribution of Had/EM for inclusive and W electrons is shown in Figure 2.4(f). As expected, the W electrons and the inclusive electrons have a different Had/EM shape.

2.4.10 Calorimeter Isolation

This cut is not an electron identification cut but a topology cut. Electrons from W and Z^0 decay are expected to be "isolated." That is, they are not expected to be produced in association with other particles. As mentioned above, electrons from other physics processes are produced associated with jets of other particles nearby in η–ϕ space. We use the "isolation" variable, *Iso*, in order to select electrons not associated with other hadronic activity. The *Iso* variable is defined as:

$$Iso = \frac{E_T^{Cone} - E_T^{Cluster}}{E_T^{Cluster}}$$

where E_T^{Cone} is the sum of the EM and Had transverse energies in all of the towers (including the electron cluster) in a radius of $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$ centered around the electron cluster, and $E_T^{Cluster}$ is the electromagnetic transverse energy in the electron cluster. The variable *Iso* for inclusive electron candidates and for electrons from W decays is shown in Figure 2.4(g). Again, the shapes are different, the inclusive electrons being less isolated.

2.5 Plug Electron Identification

The track-finding efficiency for tracks in the Central Tracking Chamber falls rapidly in the range of η covered by the plug calorimeters. Consequently, information from the CTC in the region covered by the plug calorimeters is not used in this analysis. To identify the presence of charged tracks pointing toward the cluster, the occupancy in the vertexing chamber (VTX) octant pointing towards the electron cluster is used (see Figure 2.10). This variable is the ratio of layers in the VTX on which the electron deposits charge divided by the expected number of layers in the VTX to be traversed by the electron, given the electron's trajectory. The ratio

Had/EM is used, as is the isolation variable, *Iso*. The variable χ^2_{3x3} is used. This variable is a fit of the lateral sharing of energy in the 3 towers in η by the 3 towers in ϕ around the electron cluster's center to the shape expected from test beam data. The distributions of these variables for $Z^0 \rightarrow e^+e^-$ events with a central electron and a plug electron are shown in Figure 2.10.

2.6 Forward Electron Identification

Electrons in the regions covered by the forward calorimeters are identified solely by the Had/EM, *Iso*, and VTX Occupancy variables. No other tracking or lateral sharing variables are used. The distributions of these variables for $Z^0 \rightarrow e^+e^-$ events with a central electron and a forward electron are shown in Figure 2.11.

2.7 Central Electron Trigger

A three-level multipurpose trigger[22] is used to select $p\bar{p}$ events for analysis. The first two levels are programmable hardware triggers, while Level 3 is a software trigger. This section describes the trigger selection for central electrons.

In the Level 1 trigger, energies in physical calorimeter towers of 0.1 × 15° in η-ϕ space are first summed into 0.2 × 15° trigger towers. One trigger tower is required to satisfy $E_T > 7$ *GeV*. It also requires a coincidence of hits in the two BBC's. As shown in Figure 2.12, the efficiency of this trigger for fiducial electrons is 99.2 ± 0.1 % for electrons with $E_T > 10$ *GeV*.

Level 2 performs a cluster search and matches clusters to CTC tracks. EM trigger towers with $E_T > 9$ *GeV* are cluster seeds. Adjacent EM towers are then added to the cluster if they have $E_T > 7$ *GeV*. A cut of (EM+Had)/EM < 1.125 is imposed on electron candidate clusters. A hardware track processor[23] ("Central Fast Tracker," or CFT) searches for tracks in the r-ϕ plane in the CTC. For the electron trigger, a track of $P_T > 9.2$ *GeV/c* is required to point to the electromagnetic cluster. As shown in Figure 2.12, the Level 2 efficiency is flat vs. E_T in the region of our concern (the threshold is at 9 *GeV*). The inefficiency of this trigger for W and Z^0 electrons is dominated by the CFT track reconstruction. This efficiency decreases at large $|\eta|$, as shown in Figure 2.13. The overall efficiency of this trigger for W and Z^0 electrons in the fiducial volume was 91.5 ± 0.3 % for this run.

In the Level 3 electron trigger, an electron cluster is required with $E_T > 18$ GeV. A three-dimensional track with $P_T > 13$ GeV/c is required to point to the electron cluster. The cuts $Lshr < 0.2$, $|\delta x| < 3$ cm, and $|\delta z| < 5$ cm are imposed. For this run, the average Level 3 trigger efficiency for electrons in the fiducial volume is 98.2 ± 0.1 %.

In addition to the electron triggers described above, a set of backup triggers were implemented which select $W \rightarrow e\nu$ events based not on the electron, but on the neutrino, or $\not{E}_T$ (see Section 2.8). These backup triggers require the presence of a neutrino, or $\not{E}_T$, greater than 25 GeV, and either a calorimeter cluster or a high-P_T track. These triggers are used to study the efficiency of the electron identification cuts in the trigger.

2.8 Neutrino Identification

The calorimeter response to the total activity in the event determines the resolution on the measurement of neutrino P_T, which is inferred by invoking momentum conservation. A non-interacting neutrino in our detector is detected by the presence of a large transverse momentum imbalance ("missing E_T," or $\not{E}_T$). The missing E_T is calculated from

$$\not{E}_T = |(-1) \times \Sigma \vec{E}_T^{\,i}\,|$$

where $\vec{E}_T^{\,i}$ is a vector whose magnitude is the transverse energy in a calorimeter tower and whose direction points from the event vertex to the center of the calorimeter tower. The sum is performed within the region $|\eta| < 3.6$.

Events with perfect momentum balance and no resolution effects would have $\not{E}_T = 0$. The smearing about 0 on each component (x and y) of $\not{E}_T$ is gaussian and grows with the ΣE_T in the calorimeter, as is shown in the minimum bias trigger sample of Figure 2.14. Minimum bias triggers require only a coincidence of hits in both the forward and backward BBC's to signal the presence of an inelastic event. No requirements of the calorimeters are made. The ΣE_T is the scalar sum of E_T over all towers in the calorimeter with $|\eta| < 3.6$. At the ΣE_T typical of W events, the resolution on $\not{E}_T$ is on the order of 3 GeV, while the neutrino P_T is of order 20 - 40 GeV. The $\not{E}_T$ significance, $S \equiv \not{E}_T/\sqrt{\Sigma E_T}$, is a measure of how many standard deviations away from zero is the $\not{E}_T$ in a particular event. Figure 2.15 shows S for minimum bias events and for the W candidate events in our sample.

3. Inclusive Electron Sample

Inclusive high-P_T electrons are produced in decays of the electroweak bosons, such as $W \to e\nu$, $Z^0 \to e^+e^-$, or $Z^0 \to \tau^+\tau^-$ and $W \to \tau\nu$, where one of the τ's decays to an electron. High-P_T electrons are also produced in QCD processes, where the electron is embedded in a high-P_T jet of hadrons. The processes that can produce an electron cluster in hadronic jets are (1) electrons which come in e^+e^- pairs, either from photon conversions or Dalitz decays; (2) semileptonic decays of heavy quarks, $b \to ce\nu$ or $c \to se\nu$, and (3) hadron showers ("fakes") that pass our electron identification cuts. The hadrons which pass our electron identification cuts are predominantly overlaps of $\pi^\pm$ and π^0 showers and pion charge exchange, $\pi^\pm + N \to \pi^0 + N$, which can occur in the calorimeters. This section describes the selection of a sample of inclusive electrons and of three sub-samples: a sample of electrons from W decays, a sample from Z^0 decays, and a sample of non-W/Z^0 electrons. The non-W/Z^0 sample is used as a control sample to study the W backgrounds from hadron jets. Sections 4, 5, and 6 will describe these samples further and discuss the cross-contamination between them.

Candidate events for $W \to e\nu$ and $Z^0 \to e^+e^-$ decays are selected from a common sample of inclusive high-P_T electrons located in the central detector region which pass tight cuts. Requiring tight cuts on the central electron in W and Z^0 decay serves three purposes. First, the well-understood central region has added information from the tracking and the strip chambers that can be used to suppress backgrounds from other physics processes. Second, the tight cuts on the central electron allow us to place loose, highly efficient cuts on the second lepton (the neutrino in the case of W decays and the second electron in the case of Z^0 decays). Third, and perhaps most importantly, selecting both W and Z^0 candidate events from a common sample of inclusive electrons cancels several systematic uncertainties in the ratio of the W and Z^0 cross sections.

3.1 Central Electron Selection

The selection criteria for a high-P_T, central, tight electron are listed in Table 3.1. In addition, we define a tight, *isolated* central electron as one which passes the cuts listed in Table 3.1 and also has $Iso < 0.1$ (see Section 2.4.10). Iso is not an identification variable, but an event topology cut. W and Z^0 electrons are expected to be isolated, but electrons from other physics processes may not be. A total of 50861 events pass the tight electron event selection criteria in an exposure of 19.6 pb^{-1}. A total of 30349 of these electrons pass the tight, isolated electron event cuts. The E_T spectra of the tight electrons and the isolated tight electrons are shown in Figure 3.1. A peak at 40 GeV from W and Z^0 decays is already apparent.

Table 3.1: Inclusive Central Electron Cuts

E_T	$>$			20 GeV
0.5	$<$	E/p	$<$	2.0
$Lshr$	$<$			0.2
χ^2_{strip}	$<$			10.0
$\lvert\delta x\rvert$	$<$			1.5 cm
$\lvert\delta z\rvert$	$<$			3.0 cm
$\frac{\text{Had}}{\text{EM}}$	$<$			$0.045 + 0.055\left(\frac{E\ (GeV)}{100}\right)$
$\lvert Z_{vertex}\rvert$	$<$			60 cm
Electron triggers the event				

3.2 Z^0 Sample Selection

Z^0 candidates are selected from the inclusive electron sample by requiring that the tight central electron be isolated and also requiring a second isolated electron which passes loose selection criteria. The loose cuts on the second electron are listed in Table 3.2.

Table 3.2: Z^0 Selection Cuts

-One tight, isolated central Electron		
-Second Electron passing loose cuts:		
Central:	Plug:	Forward:
$E_T > 20\ GeV$	$E_T > 15\ GeV$	
Had/EM < 0.1	Had/EM < 0.1	$E_T > 10\ GeV$
$Iso < 0.1$	$Iso < 0.1$	Had/EM < 0.1
Opposite sign charged track	$\chi^2_{3\times3} < 3.0$	$Iso < 0.1$
$E/p < 2.0$		
$66\ GeV/c^2 < M_{(ee)} < 116\ GeV/c^2$		

Figure 3.2 shows the invariant mass distribution of electron pair candidates before and after the cuts of Table 3.2 are imposed. The electron pairs before the cuts of Table 3.2 are imposed consist of one tight isolated central electron (Table 3.1) and a second cluster as defined in Section 2.2. The dominant background suppression comes from the kinematic cuts on the second electron. We observe 1312 events which fall in the 66 - 116 GeV/c^2 mass range. Figure 3.3 shows the distribution in η of the second lepton of the 1312 Z^0 candidates. Table 3.3 shows that the distribution in η of the second lepton corresponds well to expectations from the Monte Carlo when the different total detector efficiencies and backgrounds are taken into account. The Monte Carlo is normalized to the Z^0 signal.

Table 3.3: Z^0 Yield in Different Detector Regions

Detector in which 2nd Lepton Falls	Z^0 Candidate Yield	Z^0 Background (see Sect. 6)	Z^0 Signal (Yield - Background)	Monte Carlo Expectation (see Sect. 7)
Central	529	1 ± 1	528 ± 23	535 ± 13
Plug	640	14 ± 14	626 ± 29	618 ± 13
Forward	143	6 ± 3	137 ± 12	138 ± 8

3.3 *W* Sample Selection

To select *W*'s from the inclusive electron sample, we (a) require a tight, isolated central electron in the event; (b) require $\not{E}_T > 20\ GeV$; (c) reject Z^0 decays by asking that the event does not posses a second, isolated, electromagnetic cluster which forms a mass with the first electron in the 66 - 116 GeV/c^2 range. Figure 3.4 shows the *Iso* of the electron in the event *vs.* the $\not{E}_T$ in the event. The *W*'s appear as a cluster at low *Iso*, high $\not{E}_T$. The $\not{E}_T$ spectrum of the isolated ($Iso < 0.1$) and non-isolated ($Iso > 0.3$) tight inclusive electrons is shown in Figure 3.5. A total of 13796 events have $\not{E}_T > 20\ GeV$ and pass our Z^0 rejection cuts. Figure 3.6 shows the distribution in η of the electrons from the W candidates. The Z^0 removal cut removes only 41 events, because the missing E_T requirement strongly suppresses the Z^0's.

3.4 Non-W/Z^0 Electron Sample Selection

The W and Z^0 samples selected above are contaminated by electrons from other physics processes. The backgrounds of electrons from hadron jets are particularly important to understand. This section describes the selection of a control sample of those electrons from hadron jets. In Section 4 we examine the make-up of this sample and determine the fractions, f_{conv}, f_b, and f_{fake} of electrons in jets that come from conversions, heavy quarks, and fake electron clusters. The techniques used in Section 4 are then employed in Section 5 to determine the contamination of the $\not{E}_T > 20\ GeV$ sample (W sample) from these hadronic processes.

From the inclusive electron sample of 50861 events, events which have a second cluster which passes cuts of Had/EM < 0.1 and $Iso < 0.1$ are removed in order to reject electrons from $Z^0 \to e^+e^-$ and Drell-Yan pair production. Approximately 4600 events are removed by this cut. Events which have $\not{E}_T > 10\ GeV$ are rejected in order to remove electrons from $W \to e\nu$ or $W \to \tau\nu \to e\nu\nu\nu$. 21637 events survive this cut. The contamination of this sample from $W \to e\nu$, $Z^0 \to e^+e^-$, $W \to \tau\nu$ or $Z^0 \to \tau^+\tau^-$ is estimated[24] to be 1.0 ± 0.2 %. Finally, we require a hadronic jet with $E_T > 10\ GeV$ and electromagnetic fraction less than 0.8, which reduces the fraction of electrons from weak boson decays to 0.4 ± 0.1 % of the sample. The 17805 electrons passing all of these cuts are used as our control sample of non-W/Z^0 electrons.